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Tectonopalaeogeography and palaeotectonics

Palinspastic reconstruction and geological evolution of Jurassic basins in Mongolia and neighboring China

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Abstract The important event in Jurassic tectonics in Mongolia was the subduction and closure of the Mongolia-Okhotsk ocean; correspondingly, basin evolution can be divided into two main stages, related to the orogeny and collapse of the orogenic belt, respectively. The developing of Early−Middle Jurassic basins to the north of the ocean resulted from back-arc extension. The fossil sutures, from the China−SE Asia sub-continent to the south of the ocean, were rejuvenated by subduction-related orogeny; in addition, the Yanshanian intra-continental movement occurred. Three Early−Middle Jurassic molasse basins were developed by movement in Inner Mongolia, all of which stretched westwards (or northwards) into Mongolia; therefore, the molasse basins in eastern and southern Mongolia had the same geometric and kinematic features as the basins in the Inner Mongolia. Owing to the collapse of the Mongolia-Okhotsk orogenic belt, a group of rift basins developed during the Late Jurassic. In eastern Mongolia, the NE orientated extensional basins were controlled by the neogenic NE-structure. The contemporary basins in southern Mongolia and the neighboring areas in China were constrained by remobilization (inherited activation) of the latitudinal or ENE-directional basement structures. Three stages can be recognized in the evolution of the Early−Middle Jurassic basins after reversal; the basins also experienced four episodes of reformation.

Key words back-arc extension, molasse basin, collapse rift, basin evolution, basement structure, neogenic structure, Jurassic, Mongolia and neighboring China

1 Introduction

The Jurassic system is widely distributed in Mongolia and its environs; especially, the Lower-Middle Jurassic series contains coal-bearing strata of great economic value. Up to now, the Jurassic primary sedimentary basins in Mongolia have not been reconstructed; in addition, ideas regarding the tectonic settings for these basins are controversial. For example, there are two completely different opinions about Early−Middle Jurassic basins bordering China and Mongolia. Hendrix *et al*. (1996) claimed that intra-continental compressive deformation occurred continuously from the latest Late Paleozoic to the Middle Jurassic based on the nonmarine strata of the Upper Permian−Lower Jurassic (?) and the unconformity between the Lower−Middle Jurassic and the Upper Jurassic−Lower Cretaceous in the Noyon Uul region of the South Gobi (Ömnö Govi) province. Afterwards, Hendrix *et al*. (2001) and Lamb *et al*. (2008) suggested that crustal contraction took place in North China, Northwest China and southern Mongolia during the Triassic−the Jurassic with a compressive stress field, which resulted in the closure of the Paleo-Asian ocean during the latest Permian, and the succeeding collision between the Mongolia and China continents, which persisted from the Triassic to the Jurassic. Graham *et al*. (2001) pointed out that the Khamarkhoovor Formation of the Lower−Middle Jurassic in the East Gobi

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(Dorno Govi) Basin is a molasse formation. Meanwhile, there exists an opposite opinion, namely, a tensile or transtensile tectonic setting for the Jurassic basins. Kimura *et al*. (1990) suggested that the Mesozoic basins in East Asia were controlled by the tenso-shear fractures related to the collision-extrusion structures. Ritts *et al*. (2001) demonstrated that the Lower Jurassic strata in the western Daqing Shan of the Yinshan Mountains, Inner Mongolia, are deposited in a rift basin. In addition, the Yagan-Onch Hayrhan metamorphic core complex bordering China and Mongolia supports further evidence for extension (Webb *et al*., 1999). Wang *et al*. (2002) proposed that the extension structure controlling the metamorphic core complex started, at least, from the latest Early Jurassic and continued to the Late Cretaceous.

In the light of tectonopalaeogeography (Feng, 2003, 2009; Feng *et al*., 2012) and orogen-palaeogeography (Wu, 2005, 2007), and based on a study of the regional tectonic framework, this paper will focus on the palinspastic reconstruction of the Early−Middle Jurassic and the Late Jurassic primary basins respectively, and will approach the tectonic setting of the basins and related geological evolution.

2 Regional tectonic framework

Structurally, Mongolia is attached to the Central Asian Orogenic Belt, to the north and the south of the orogenic belt are the Siberian and Sino-Korean subcontinents (cratons) respectively. The orogenic belt grew out of the Paleo-Asian ocean, which was a wide archipelago occurring in the Neoproterozoic and Paleozoic. Because of multiple and varied directional subductions of the oceanic crust during the geo-history, accompanied by multiple arc-arc (continent) collisions (Wu, 1998; Windley *et al*., 2001), both subcontinents were accreted and enlarged successively. By the end of the Permian, the Paleo-Asian ocean was closed (Heubeck, 2001), followed by the collision of the two subcontinents in the Triassic.

The Sino-Korean subcontinent to the south of the Paleo-Asian ocean was enlarged northwards by accretion of a series of arc terrains from the Paleozoic to the Triassic. The simultaneous closure of the Qinling-Dabie ocean in central China and the Paleotethyan ocean in southwestern China, and the following collision and amalgamation of the Sino-Korean, the Yangtze and the Shan-Thai subcontinents resulted in the creation of the China-SE Asia subcontinent (Wu, 1997). The latter was still surrounded by oceans: to the southwest was the Neotethyan ocean, to the north was the Mongolia-Okhotsk ocean (Zorin *et al*., 1993), and to the east was the Panthalassa (or Paleo-Pacific) ocean (Wu and Yano, 2007) respectively.

During the Early Mesozoic in Mongolia and adjacent areas of Russia, the key structure was the Mongolia-Okhotsk ocean, which stretched eastwards and linked up with the Panthalassa. The ocean subducted northwards and closed in the latest Early Jurassic−early Middle Jurassic (Zorin, 1999). According to this theory, the evolution of Jurassic basins in Mongolia can be divided into two main periods, related to the orogeny during the Early−Middle Jurassic and to the collapse of the orogenic belt during the Late Jurassic respectively.

The tectonic setting of Early−Middle Jurassic basins in northern Mongolia, specifically, to the north of the Mongolia-Okhotsk suture zone, was different when compared to the basins in central−southern Mongolia which was situated to the south of the suture zone. In total, the Mongolia-Okhotsk ocean subducted northwards under the accreted Siberian subcontinent. The northern part of Mongolia was located in a back-arc region and the development of the basin was constrained by back-arc extension. Erdenetsogt *et al*. (2009) reported that the coal-bearing nonmarine Saikhan Formation of Lower−Middle Jurassic age filled about twenty scattered grabens that might indicate a group of isolated small basins related to the initial subduction of the oceanic crust and occurred in the back-arc region of an Andean-type mountain arc. These scattered grabens were further developed with the ongoing subduction and superimposed by a unified large (fault-) depression, named the Orhon-Selenge Basin in the Figure 1. The southwestern and the southeastern boundaries of the basin, being NW- and NE-running respectively, were close to and parallel to the Mongolia-Okhotsk suture zone. The sediments in the basin of the Saikhan Formation, 670 m thick (Table 1), is characterized by thick conglomerates in the lower member with a thickness of 250 m. The upper member of the formation consists of sandstone, siltstone and shale with interlayers of coal seams.

To the south of the suture zone existed an amalgamated continental mass, namely, the China-SE Asia subcontinent. It is a composite entity, welded and combined by a series of cratons and massifs. The fossil sutures and deep fractures within the composite continent represent active tectonic zones, which will be rejuvenated and will control the intra-plate (intra-continental) orogeny in the case of the inter-plate orogeny occurring on the outer side of the composite continent (Wu, 2000, 2002). In Inner Mongolia and adjacent areas, there are four fossil sutures; three of them relate to the present study; they are, from South to North, the Caledonian Bayan Qagan-Ondor Sum-Kedanshan suture, the Hercynian Solen Mountain-Erlian-Hegen Mountain suture, and the Hailar-Huma suture (Wu, 2006). Subduction and related closure of the inter-plate orogeny of the Mongolia-Okhotsk ocean immediately re-activated all fossil sutures; at the same time, intra-continental orogenies occurred, which are called the Yanshanian movement in China. Each Yanshanian orogenic belt (fold-and-thrust belt) constrained a molasse basin (Fig. 1) that are called the Yinshan-Yanshan, the Erlian and the Hailar Basins respectively (Wu, 2007; Wu *et al*., 2008a).

It should be pointed out that the Mongolia-Okhotsk suture zone consists of NE- and NW-striking segments in the Mongolian territory. The former one experienced a complete tectonic cycle from oceanic crust creation to subduction-collision orogeny during the latest Paleozoic to the Early Mesozoic, which constrained the development of Jurassic basins in eastern Mongolia. Along the NW-striking segment of the suture zone, only one ophiolite, namely, the Adaatsag ophiolite, was defined with a zircon U−Pb age of 325.4±1.1 Ma (Early Carboniferous; Tomurtogoo *et al*., 2005). The Hangay area was uplifted during the Permian; in addition, the NW-striking segment might be transpressional and acted as the transitional zone in compressive-contracted events since the Permian. It may have become a left-lateral shearing fracture in the Early-Middle Jurassic (Tomurtogoo *et al*., 2005) and constrained transpressional fractures in western Mongolia to orientate in a northwest direction. The major basin-controlling faults thrust northwards (or northeastwards) in western Mongolia (for example, the Shinejinst Basin, Wu, 2013). The geodynamics of the Jurassic thrusting in western Mongolia, eastern Junggar of Xinjiang and Beishan (North Mountains) of northern Gansu might have resulted from the closure of the Jurassic Tethyan oceans and followed continent-continent collision in western China (Vincent and Allen, 2001; Lamb *et al*., 2008), which produced a northward push-

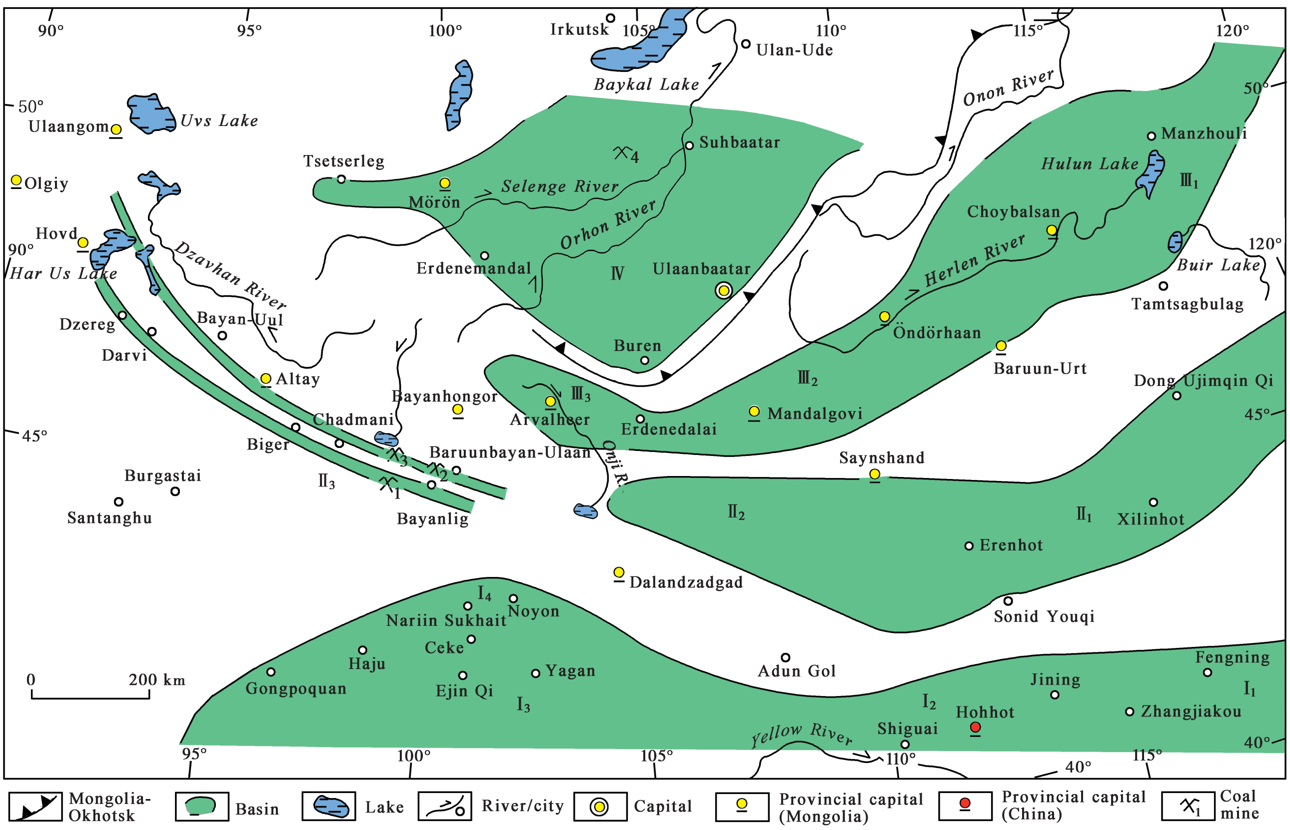

Fig. 1 Distribution of Early−Middle Jurassic basins in Mongolia and adjacent areas in China (based on present geographic position). Basin names: I_1−Yanshan; I_2−Yinshan; I_3−Yingen; I_4−The South Belt Molasse Basin; II_1−Erlian; II_2−The eastern sector of Middle Belt Molasse Basin; II_3−The western sector of Middle Belt Molasse Basin; III_1−Hailar; III_2−The eastern sector of North Belt Molasse Basin; III_3−The western sector of North Belt Molasse Basin; IV−The Orhon-Selenge Basin. Coal mine names: 1−Shinejinst; 2−Lhk Bogd; 3−Alug Tsaluir; 4−Ulaan ovoo (near the Mongolia−Russia boundary).

compression. This paper will focus on the Early−Middle Jurassic basins in eastern Mongolia, whose evolution must be a response to the subduction orogeny of the NE-striking segment of the Mongolia-Okhotsk ocean.

3 Early−Middle Jurassic molasse basins

3.1 Yanshanian molasse basins in northern China

The Yinshan-Yanshan molasse belt, with a nearly latitudinal orientation, can be separated into three segments. The eastern sector is the Yanshan Basin, characterized by violent volcanic activity. The middle segment is the Yinshan Basin, where the Wudanggou Formation ($J_{1-2}w$, coal-bearing clastic sediments), the Changhangou Formation (J_2c), and the Daqingshan Formation (J_3d, red beds) were deposited. The western one includes the Yingen Basin in Alxa area and the Chaoshui Basin in the border region of Alxa and Gansu; the stratigraphic records of the latter are shown in Table 1. The Jijigou Formation consists of conglomerate in the lower, sandstone in the middle and lacustrine mudstone in the upper part, with interlayers of andesitic-basaltic lava, which is covered, unconformably or disconformably, by the Qingtujing Formation consisting of coal-bearing detrital sediments. The Late Jurassic red or varicolored clastic rocks, named the Shazaohe Formation, were continuously deposited on the Qingtujing Formation (Li, 1996).

North of the Yinshan-Yanshan molasse belt is the Erlian Basin, whose eastern end is located in Longjiang-Daqing, Heilongjiang Province, with the sediments being named the Daqing Group (J_2d; Zhu *et al*., 2007). In Ulanhot-Xilinhot region of Inner Mongolia (Table 1), the Lower-Middle Jurassic constitutes the Hongqi Formation (coal-bearing detrital rocks) and the Wanbo Formation (coal-bearing fine-grained sediments), which is unconformably covered by the acidic lava of Manketou Obo Formation (J_3mk; Li, 1996).

Further northwards, the Jurassic in the Hailar Basin is named the Xing′anling Group, unconformably deposited on the Budate Group of Triassic (Chen *et al*., 2007). It can be divided into three members (Table 1). The majority of the lower member consists of intermediate-acidic volcanic rocks, with a SHRIMP U−Pb age of 164.2±3.7 Ma (Zhang, 2007). The middle member consists of clastic sediments interbedded with coal layers. The upper member is (intermediate−) basic volcanic rocks; with dates of 150−140 Ma (Zhang, 2007) that indicate that the eruption lasted from the Late Jurassic to the Early Cretaceous.

3.2 Molasse basins in central-southern Mongolia

All three Yanshanian molasse basins mentioned above in northern China stretch westwards (or northwards) into central-southern Mongolia.

The western sector of the Yinshan-Yanshan Basin (the Yingen Basin) extends northwards into the southwestern part of South Gobi (Ömnö Govi) Province, Mongolia. For

Table 1 Jurassic strata and their correlation in the basins bordering China and Mongolia

System	Series	Chaoshui Basin	Erlian Basin	Eastern sector of Middle Belt M.B.	Western sector of Middle Belt	Hailar Basin		Western sector of North Belt M.B.	Orhon−Selenge Basin
Jurassic	Upper	Shazaohe Fm.	Bayan Golao Fm. Manitu Fm. Manketou Obo Fm.	Sharilin Fm. 155 ± 1 Ma		Xing′anling Group	Upper Member	Dorgot Fm.	
							Middle Member		
	Middle	Qingtujing Fm.	Wanbao Fm.	Khamarkhoovor Fm.	Jargalant Fm.		Lower Member 164.2 ± 3.7 Ma	Bakhar Fm.	Saikhan Fm.
	Lower	Jijigou Fm.	Hongqi Fm.						

Fm. = Formation; M.B. = molasse basin

For the stratigraphic columns of the Saikhan, Bakhar and Jargalant Formations, see Erdenetsogt *et al.* (2009); for the Khamarkhoovor Formation, see Graham *et al.* (2001), the Xing′anling Group, see Chen *et al.* (2007); and for others, see Li (1996), respectively.

example, the Lower−Middle Jurassic strata outcrop in the Noyon area and unconformably overlain by the Upper Jurassic−Lower Cretaceous strata (Hendrix *et al*., 1996). From the Nariin Sukhait coalfield to the west of Noyon, the Lower−Middle Jurassic strata can be conserved in the lower walls of thrusts. The strata are bounded to the northeast by the Gobi-Altai (Govi-Altay) range. We name this the South Belt Molasse Basin of Mongolia (Fig.1), although it occupies a relatively small area.

The westward elongation of the Erlian Basin is named the Middle Belt Molasse Basin of Mongolia (Fig.1), which can be divided into two segments by the Triassic−Jurassic upwarped district between the east longitude 102°and 104°. In the eastern sector, the J3−K1 Khamarkhoovor Formation (Table 1) outcrops on some sub-order fault-rise rifts of the Late Jurassic−Cretaceous, such as the Middle Gobi (Dung Govi) and the East Gobi (Dorno Govi) Basins. The sedimentary environment of the Khamarkhoovor Formation with an upward-fining succession is a sandy braided river course; then, it changes to diluvial plain and swamp of a snaking stream (Graham *et al*., 2001).

The western sector of the Middle Belt Molasse Basin, being nearly NW-striking and controlled by the basement structure, is split into two relatively narrow sub-belts. The south sub-belt (the eastern end of which is to the southeast of Bayanlig) passes northwestwards through Shinejinst, Biger, Darvi, Dzereg to the south of the Har Us Lake (Fig.1). The Shinejinst and Dzereg Basins are famous post-structural basins along the south sub-belt; the former one was discussed in another paper (Wu, 2013). The Dzereg Basin is sandwiched between two ranges: to the southwest is Baataryn Nuruu and to the northeast is Jargalant Nuruu respectively; the Jargalant Nuruu separates the Dzereg Basin at the Valley of Lakes towards the northeast. The palaeocurrents indicate there were two source regions providing detritus (Howard *et al*., 2003), which might constrain the Dzereg Basin as a transpressional one bounded by two transpressional fractures on both its sides. The north sub-belt starts at the southeastern side of the Baruunbayan-Ulaan and it elongates northwestwards from the Lhk Bogd and Alug Tsaluir coal mines, through north of Chandmani, south of Altay, Bayan-Uul, to the north of the Har Us Lake (Fig. 1). Geomorphologically, the middle and northwestern sectors of the north sub-belt are named as the Valley of Lakes and the Valley of Great Lake respectively.

The Lower−Middle Jurassic in the western sector of the Middle Belt Molasse Basin is named the Jargalant Formation (Table 1). It is similar to the Saikhan Formation in the Orhon-Selenge Basin, and is composed of conglomerates in the lower member and coal-bearing finer clastic sediments in the upper member, with the total thickness less than 1400 m (Erdenetsogt *et al*., 2009). The Jargalant Formation in the Dzereg Basin with the thickness of 1180 m consists of gray and red conglomerates in the lower member and polymictic sandstones with occasional coal horizons in the upper member; the conglomerates are distributed mainly in the southern part of the basin (Howard *et al*., 2003).

The extended part of the Hailar Basin is named the North Belt Molasse Basin of Mongolia (Fig.1), which can be divided into two sectors according to the orientations. The eastern sector is ENE-striking, whose eastern part is superimposed by the Late Jurassic−Cretaceous rift basins. The western sector is NW-striking, parallel to the western segment of the Mongolia-Okhotsk suture zone (Zorin, 1999). The Lower−Middle Jurassic in the western sector is named the Bakhar Formation (Table 1), which is characterized by poly-interlayers of pyroclastic rocks (Erdenetsogt *et al*., 2009), indicating tectonic mobility related to subduction of the Mongolia-Okhotsk ocean.

4 Late Jurassic basins

The Late Jurassic basins in Mongolia developed mainly in the eastern part of the country and the southmost part of neighboring China. In western and northern Mongolia, only a few small and isolated intermontane basins without regular orientation are present.

4.1 Basins in eastern Mongolia

Some researchers discussed Early Cretaceous coal-bearing basins in eastern Mongolia, which superimposed the Late Jurassic basins, except the Tamsag Basin (Graham *et al*., 2001; Dill *et al*., 2004; Erdenetsogt *et al*., 2009). In other words, the Tamsag Basin might have been created during the Early Cretaceous by the southward elongation of the Hailar Basin from Inner Mongolia, China. There are six Late Jurassic basins in eastern Mongolia: the Choyr-Nyalga, Onon, Choybalsan, Sukhbaatar, Central Gobi and East Gobi Basins (Fig.2). The Upper Jurassic in the former two basins is named the Dorgot Formation (Kosbayar, 1996), with an age of Tithonian−Kimmeridgian. In southeastern Gobi area, the Upper Jurassic in the basins is called the Sharilin Formation, which was once regarded as Tithonian−Kimmeridgian (Yamamoto *et al*., 1993). However, the orange-colored tuffaceous sandstone from the upper part of the formation yielded a $^{40}Ar-^{39}Ar$ age on biotite of 155±1 Ma, indicating that the formation was deposited during the Oxfordian stage (Graham *et al*., 2001).

The Sharilin Formation is an overall upward-fining siliciclastic succession with a thickness of 1350 m at the Har Hotol sub-rise of the East Gobi Basin. The basal 200−300 m of the formation consists of pebble to cobble conglomerate, which were the deposits of braided streams or the upper reaches of stream-dominated fan systems. The middle part of the formation contains red and green mudstones with some nodular carbonate horizons. The sediments of the upper part, as a progradational delta on a lacustrine shoreline, consisted of polycycles of upward-coarsening clastic rocks (Graham *et al*., 2001). The Upper Jurassic is recorded as a rift basin, and it is regarded as a synrift sequence 1 (SR−1; Graham *et al*., 2001; Johnson, 2004).

This paper emphasizes some new important ideas as follows:

1) The Late Jurassic basins in eastern Mongolia are NE-orientated and are constrained by the Mongolia-Okhotsk suture zone. It stretches from Russia where the suture zone is located along the Shilka River to the northwest of the Onon River. In Mongolia, it stretches to the east of the NE-striking Khentey Range; it turns at Addatsag, northwestwards to the Hangay Mountains (Zorin, 1999). Namely, the east segment of the suture zone is NE-striking.

2) The Mongolia-Okhotsk ocean subducted northwards (Zorin, 1999), thus, a NE-orientated fold-and-thrust belt occurred widely in eastern Mongolia during the period of subduction of the ocean and the subsequent continent-continent collision. The NE-orientated structure is a neogenic one that appeared in the Late Jurassic. In other words, the formation and the evolution of Late Jurassic basins in eastern Mongolia are controlled by neogenic fractural structures, distinctly different from the Early−Middle Jurassic basins that were constrained by the basement or pre-existing structures.

3) The Late Jurassic basins were created by an extensional stress field; the nature of basin should be a rift basin that resulted from collapse of the Mongolia-Okhotsk subduction−collision orogenic belt. A regional unconformity interface separates the Upper Jurassic from the Lower-Middle Jurassic, indicating that Jurassic basin evolution experienced two major periods that were related to the orogeny and collapse of the orogenic belts respectively.

4) Although the Early Cretaceous basins are extensional in nature, there is a discrepancy between them and the Late Jurassic basins in tectonic settings. Since the Late Jurassic, a series of allochthonous terrains accreted onto the margin of the NE Asian continent along the NE−orientated Tancheng−Lujiang and Changle−Nan'ao fractures; in ad-

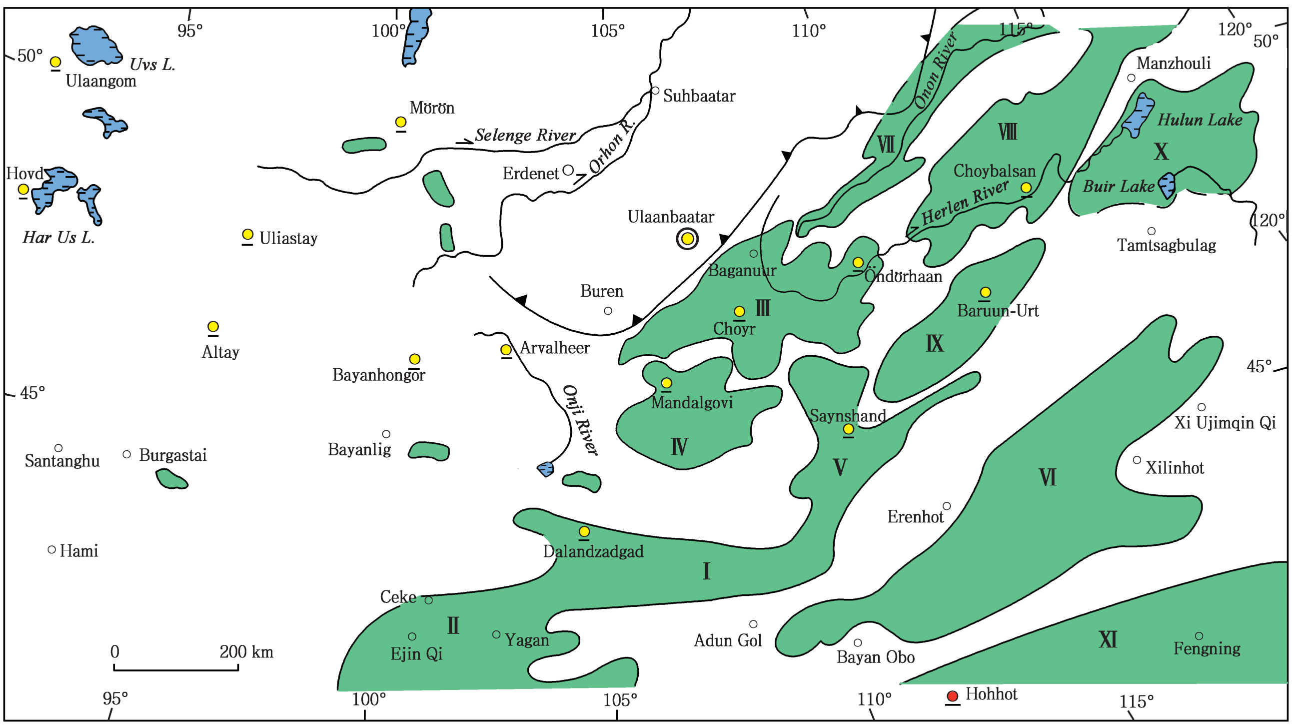

Fig. 2 Distribution map of Late Jurassic basins in Mongolia and neighboring China. Legends are the same as in Fig. 1; Basin names: I−South Gobi; II−Yingen; III−Choyr-Nyalga; IV−Central Gobi; V−East Gobi; VI−Erlian; VII−Onon; VIII−Choybalsan; IX−Sukhbaatar; X−Hailar; XI−Yinshan-Yanshan.

dition, an oblique convergence-shearing orogeny occurred successively, which covered a vast territory (Wu *et al*., 2007). Owing to accretion of the Nadanhada-Bikin, Central Sikhote-Alin, Hangali, Hida-Oki, Mino-Tamba and North Kitakami terrains (the latter three being drifted away by opening of the Sea of Japan), an oblique convergence-shearing orogenic belt took shape during the Late Jurassic (Wu and Yano, 2007), which collapsed in the Early Cretaceous and constrained a group of the NE-orientated rift basins occurring on the margin of NE Asian continent. The basin group is comprised of the Songliao Basin in Heilongjiang, NE China (Wu *et al*., 2009), the Hailar Basin enlarged southwards towards the Tamtsag region in Mongolia (Chen *et al*., 2009), and six NE-orientated basins that was mentioned above in eastern Mongolia.

4.2 Basins in southern Mongolia and neighboring China

One instance in the adjacent area in China is the Erlian Basin, where the Upper Jurassic Xing′anling Group contains alluvial and fluvial deposits with thicknesses between 1500−5000 m, which unconformably covered the Lower−Middle Jurassic Ahelalitan Group. It is an extensional basin (Meng *et al*., 2003) with the north boundary being NE-striking approximately, which should have the same tectonic setting as the simultaneous NE-orientated basins in eastern Mongolia. Meanwhile, the Hercynian ENE-directional tectonics, which constrained the evolution of Early−Middle Jurassic molasse basins, rejuvenated in the Late Jurassic, and resulted in a southern boundary of the basin to be partly ENE-striking. Furthermore, because the latitudinal structure in the basement was remobilized in the Late Jurassic, thus, the basin was shaped like a loudspeaker with an opening towards the east (Fig. 2, Wu *et al*., 2008b). There is more evidence that supports the rejuvenation of the ENE-directional tectonics, that both the Ondor Sum Rise to the south of the Erlian Basin and the Bayanbulag sub-order rise within the basin were orientated in a northeast by east direction (Liu *et al*., 2006). In brief, the development of the Late Jurassic rift basins might be controlled by inherited activations of the basement or pre-existing tectonics in addition to the neogenic NE-striking structure.

There is the Upper Jurassic Sharilin Formation in southern Mongolia, where the Lower Cretaceous is famous for the excavation of dinosaur skeletons (Shuvalon, 2003), and it is named the South Gobi Basin and the eastern sector of which is NE-orientated and joins with the East Gobi Basin. The main body of the basin stretches latitudinally, which implies the primary basin-controlling structure being W-E-striking since the W-E structure was well developed in the Hercynian orogeny (Hendrix *et al*., 1996). Unlike the NE-orientated basins in eastern Mongolia, the South Gobi Basin is principally constrained by the inherited activation of the basement structure with rich coal resources; in general, the boundaries of coal fields or mine fields are defined by latitudinal faults re-activated during the Yanshanian movement. The westward elongation of the basin joins with the Yingen Basin in Alxa, western Inner Mongolia (Fig.2).

5 Evolution of Jurassic basins in Mongolia

5.1 Formational period of Early−Middle Jurassic basins

The development of thrusting and molasse basins in the Yinshan-Yanshan region, in northern China, was studied by He *et al*. (1998). There are common characters of geometry and kinematics among the eastern sector of the North Belt Molasse Basin, the eastern sector of the Middle Belt Molasse Basin and the South Belt Molasse Basin (the Yanshan-Yanshan Basin), because their occurrence was constrained by the same basin dynamics. All of them are approximately latitudinally orientated. The main basin-controlling fracture is situated to the north of the basin and it thrusts southwards. The basin is wedge-shaped, the subsiding center of which is near the northern boundary of the basin, where the coal seams develop better.

The Orhon-Selenge Basin in northern Mongolia has a different tectonic setting compared with the molasse basins in central-southern Mongolia, so that, there are distinct lithologic and coaly records in these basins. However the sedimentary sequences of them manifest quite similar lithologies; specifically, there are thick conglomerates in the basal part with a upward-fining succession, the coal seams in the middle part of the stratigraphic column, and the coal bed at the top of each sub-order depositional cycle. Based on these similarities, the evolution of the Early−Middle Jurassic basins in northern, eastern and southern Mongolia can be divided into three stages during the formational period.

The initial basins appeared in the first stage. Several isolated grabens were created by back-arc extension from northern Mongolia to the north of the Mongolia-Okhotsk ocean. To the south of the ocean, three fossil sutures that were mentioned above in the amalgamated continent, (namely, the Bayan Qagan-Ordor Sum-Kedanshan, the Solen Mountain-Erlian-Hegen Mountain, and the Hailar-Huma sutures), were rejuvenated and controlled the developments of three molasse basins in their lower walls (Fig.3a).

Due to a violent topographic contrast, the erosion and deposition might have happened rapidly and the detrital substances might not be transported for a long distance in the stage; therefore, the sediments are mainly conglomerates with interlayers of sandstone. Generally, the thickness of conglomerate is up to a few hundreds of meters, for example, 640 m in the Dzereg Basin (Howard *et al*., 2003), more than 500 m in the South Belt Molasse Basin (Wu, 2013), and 250 m in the Orhon-Selenge Basin (Erdenetsogt *et al*., 2009). In the majority of the basins, a layer of coal streak, lenticular coal, or very thin coal bed without economic value was formed. At some localities, for instance, the Khamarkhoovor Formation in the eastern sector of the Middle Belt Molasse Basin, even the coal streak did not develop (Graham *et al*., 2001). It implies the supply of a lack of source substances for coal, which might be a climate related phenomenon, indicated by the red or varicolored conglomerates. From the viewpoint of coal geology, the stage could be called the pre-coal-forming stage.

The basins expanded in the second stage. The molasse basins expanded toward the foreland unidirectionally accompanied with the migration of the subsiding center. Within the basins, some large rivers appeared and the peaty swamps developed widely on the alluvial plains far from the river courses, as well as on the flood lands. The back-arc grabens enlarged toward its both sides, but were not linked to with each other (Fig. 3b). In the grabens, once the fluvial sediments deposited in the center and alluvial beds along the margins. With the grabens developing, the fluviolacustrine sediments were deposited, which resulted in multiple coal-forming environments in these grabens (Erdenetsogt *et al*., 2009). This stage could be named the coal-forming stage because some valuable coal fields were created.

Generally, four or five coal seams were developed, with thickness of the coal measure of less 300 m. In some localities with more tectonic mobility, for example, the Valley of Lakes, the thickness of coal measure strata is about 1100 m (Erdenetsogt *et al*., 2009). Another exception was the Ulaan Ovoo graben in the Orhon-Selenge Basin, where twelve coal seams occur, each of which is 7.8−49.6 m thick, except for the thickest one being 63 m (Erdenetsogt *et al*., 2009). Accordingly, the coal-forming stage in some basins might be divided further into several sub-stages or coal-forming episodes. In addition to a wide and relatively stable depositonal space, the suitable climate supported a situation for unprecedented lush growth of plants. The Mongolian Jurassic coals are characterized by high contents of vitrinite and liptinite, which indicates that a strongly seasonal and monsoonal climate existed (Erdenetsogt *et al*., 2009). The rise of the underground water table caused

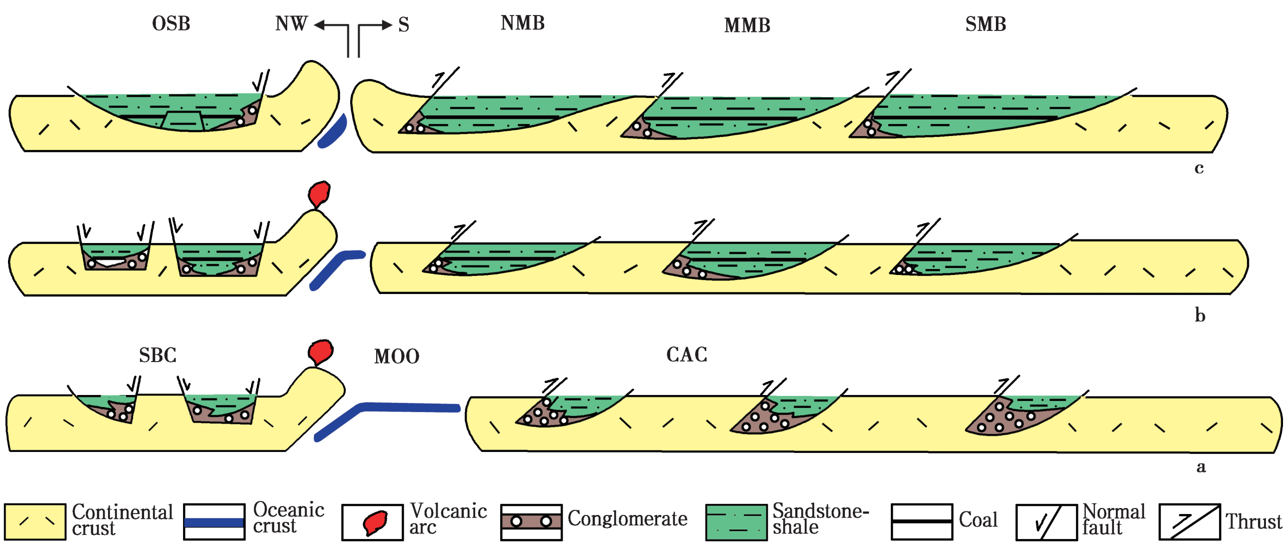

Fig. 3 A diagram of structural evolution of Early−Middle Jurassic basins in northern, eastern and southern Mongolia. Names of tectonic units: SBC−Siberian subcontinent; MOO−Mongolia-Okhotsk ocean; CAC−China-SE Asia subcontinent; OSB−Orhon-Selenge Basin; NMB−North Belt Molasse Basin; MMB−Middle Belt Molasse Basin (eastern sector); SMB−South Belt Molasse Basin. a−Pre-coal-forming stage; b−Coal-forming stage; c−Post-coal-forming stage.

the swampiness occurring frequently.

The basin developing entered a period of full bloom in the third stage. The molasse basins further expanded toward the foreland. To the north of the closed oceanic basin, the former about twenty isolated grabens were superimposed by a unified (fault−) depression, namely, the Orhon−Selenge Basin (Fig. 3c). The basin distribution of the stage was shown in Figure 1. The original basin might have covered a larger area than what is shown in the figure, for some geological records had been eroded away thoroughly.

The depositional space was further enlarged and strata with a considerable thickness were deposited during this stage. For instance, there developed the sediments, with thickness over 1000 m, above the coal measure strata in the Bakhar Formation. In the Shinejinst coalfield, although the topmost coal seam was partly eroded, the residual sedimentary record above the coal seam thickened 500 m and more. Few coal bed was deposited during the stage, so it could be called the post-coal-forming stage, which might be related to the climate change. In the latest Middle Jurassic, the climate became hot and arid (no longer humid and rainy), and the thick red beds of the Upper Jurassic were widely distributed in Mongolia and its surroundings.

5.2 Later reformation of Lower−Middle Jurassic basins

All Early−Middle Jurassic basins closed and reversed by the end of Middle Jurassic; then the basins experienced four episodes of reformation.

Due to compression deformation, the first episode of reformation resulted in tilting, thrusting and folding of the Lower−Middle Jurassic. The main thrusts inherited the vergence of previous formation and some sub-order reverse faults might have occurred as back thrusts. All these processes caused the contraction of the basin. Another effect of the episode was uplifting and erosion of the Lower−Middle Jurassic. Vassallo *et al*. (2007) suggested that the first important uplift and cooling event in southern Mongolia occurred during the Jurassic, with a vertical displacement of the crust of 2000 m. It is widely accepted that the strong uplift was related to the collision between the Siberian sub-continent and the Mongolian areas attached to the China−SE Asia sub-continent and followed the closure of the Mongolia-Okhotsk ocean (Halim *et al*., 1998; Zorin, 1999); thus, the uplifting and cooling event of the same age can be observed in southern Siberia (DeGrave and Van den Haute, 2002).

The second episode of reformation of the tilted and thrust Lower−Middle Jurassic then was buried deeply. In eastern Mongolia, the thickness of the Upper Jurassic is more than 3000 m in the depression centers (Graham *et al*., 2001); the thickness of the Lower Cretaceous (the Zuunbayan Group) is 1800 m (Erdenetsogt *et al*., 2009). In addition, there are 2−4 unconformities within the Cretaceous, indicating that the strata had been partially eroded. It might be deduced that the buried depth of the top bed of the Lower−Middle Jurassic was more than 5000 m. The Lower−Middle Jurassic series in western Mongolia was buried by the Lower Cretaceous Zuunbayan Group or Andkhdag Formation with a remaining thicknesses of 1800 m and 700 m respectively (Erdenetsogt *et al*., 2009). The Lower Cretaceous series widely occurs in northern Mongolia as well.

The Early Cretaceous epoch was an extensional period for the Mongolian territory; the third deformation of the Lower−Middle Jurassic happened during this time as normal faulting, which cut an original basin into two or several sub-basins. The coal seams in the upper wall of the fault could be preserved, whereas the coal-bearing strata in the footwall might be eroded since the vertical fault displacement could reach hundreds of meters.

The fourth episode of reformation in western and northern Mongolia was regional uplifting during the Cenozoic. The Lower Cretaceous was denuded in broad region, except for some intermontane basins such as the Dzereg Basin and the valley of the Selenge River. Remnants of the Lower−Middle Jurassic outcrop along the piedmonts of the Altay and Hangay Mountains and were covered by recent alluvial deposits. In eastern Mongolia, the Lower−Middle Jurassic might be buried once again in the areas where Cretaceous basins are superimposed by Cenozoic basins.

6 Conclusions

1) The key tectonics during the Jurassic in Mongolia and neighboring regions of Russia is the subduction of the Mongolia-Okhotsk ocean and subsequent continent-continent collision. Consequently, the evolution of the Jurassic basins can be divided into two major episodes: the Early−Middle Jurassic and the Late Jurassic, related to the orogeny and collapse of the orogenic belt respectively. During the Early−Middle Jurassic, the area to the north of the ocean was located in a stress field of back-arc extension, whereas an intra-continental orogeny occurred in a broad territory to the south of the ocean, which controlled the development of molasse basins. For the first time, this paper

has reconstructed the original distribution of the Early−Middle Jurassic and the Late Jurassic basins in Mongolia and the adjacent area in China.

2) This paper emphasizes that the molasse basins developed during the Early−Middle Jurassic; the low-angle normal faulting related to the metamorphic core complex occurred during the Early Cretaceous. The Early−Middle Jurassic molasse basins in eastern and southern Mongolia had the same geometric and kinematic features as the contemporary basins in Inner Mongolia, China. Constrained by the subduction orogeny, all Early−Middle Jurassic basins in Mongolia experienced a similar evolutional process, which can be divided into three stages: the pre-coal-forming, coal-forming and post-coal-forming stages.

3) Owing to variations of the basement structure, the syn-orogenic stress field and the basin-forming dynamics, the Early−Middle Jurassic basins in western Mongolia show different geometric and kinematic features when compared with simultaneous molasse basins in eastern Mongolia, which suggests a differentiation of regional tectonic evolution between the east and west parts of Mongolia. In the Late Jurassic, the differentiation was more noticeable; specifically, several NE-orientated extensional basins occur in eastern Mongolia, whereas the western Mongolian areas were uplifted and eroded.

4) Although compressional and contractional events of the Early−Middle Jurassic in China-Mongolia border areas are widely accepted, there are differing insights between the Chinese and Euro-American geologists. The Chinese geologists propose that the Indosinian and Yanshanian orogenies should be related to the main tectonic cycles separately; the former being an inter-plate orogeny and the latter being an intra-continental (intra-plate) one in the great territory of the China-SE Asia sub-continent, which constitutes a distinguishing feature of Chinese tectonic evolution. However, most Euro−American geologists considered that it was a continuous process of intra-continental deformation from the latest Permian to the Jurassic. Some researchers, for example, Darby *et al*. (2001) and Davis *et al*. (2001), have acknowledged that the Yanshanian movement is an intra-continental orogeny and is caused by closure of the Mongolia-Okhotsk ocean based on the detailed study of Jurassic volcanic-sedimentary formations in the Yinshan-Yanshan area.

5) The Late Jurassic rift basins are NE-orientated in eastern Mongolia, which were constrained by the neogenic structure caused by subduction and collision since the suture zone in eastern Mongolia was NE-striking. The contemporary basins in southern Mongolia and Inner Mongolia are mainly oriented latitudinally or in an ENE direction and they were controlled by remobilizations (inherited activations) of the basement or pre-existing structures.

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